

NASA TECHNICAL MEMORANDUM

NASA TM X- 71927

COPY NO.

NASA TM X- 71927

(NASA-TM-X-71927) AERONAUTICAL FUEL
CONSERVATION POSSIBILITIES FOR ADVANCED
SUBSONIC TRANSPORTS (NASA) 45 p HC
\$4.00 16

CSCL 01C

N74-20654

G3/02 Unclas
35325

AERONAUTICAL FUEL CONSERVATION POSSIBILITIES FOR ADVANCED SUBSONIC TRANSPORTS

by Albert L. Braslow and Allen H. Whitehead, Jr.

December 20, 1973

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LANGLEY RESEARCH CENTER, HAMPTON, VIRGINIA 23665

1. Report No. NASA TM X-71927		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle AERONAUTICAL FUEL CONSERVATION POSSIBILITIES FOR ADVANCED SUBSONIC TRANSPORTS				5. Report Date Dec. 20, 1973	
				6. Performing Organization Code	
7. Author(s) Albert L. Braslow and Allen H. Whitehead, Jr.				8. Performing Organization Report No.	
9. Performing Organization Name and Address NASA Langley Research Center Hampton, Virginia 23665				10. Work Unit No.	
				11. Contract or Grant No.	
12. Sponsoring Agency Name and Address NASA				13. Type of Report and Period Covered TM X	
				14. Sponsoring Agency Code	
15. Supplementary Notes Special technical information release, not planned for formal NASA publication.					
16. Abstract The anticipated growth of air transportation is in danger of being constrained by increased prices and insecure sources of petroleum-based fuel. Fuel-conservation possibilities attainable through the application of advances in aeronautical technology to aircraft design are identified with the intent of stimulating NASA R&T and systems-study activities in the various disciplinary areas. The material includes drag reduction; weight reduction; increased efficiency of main and auxiliary power systems; unconventional air transport of cargo; and operational changes.					
17. Key Words (Suggested by Author(s)) (STAR category underlined) <u>AIRCRAFT</u> , FUEL CONSERVATION				18. Distribution Statement Unclassified - Unlimited	
19. Security Classif. (of this report) Unclassified		20. Security Classif. (of this page) Unclassified		21. No. of Pages 16	
				22. Price* \$4.00	

* Available from { The National Technical Information Service, Springfield, Virginia 22151
STIF/NASA Scientific and Technical Information Facility, P.O. Box 33, College Park, MD 20740

ABSTRACT

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Langley Research Center

SUMMARY

The anticipated growth of air transportation is in danger of being constrained by increased prices and insecure sources of petroleum-based fuel. Fuel-conservation possibilities attainable through the application of advances in aeronautical technology to aircraft design are identified with the intent of stimulating NASA R&T and systems-study activities in the various disciplinary areas. The material includes drag reduction; weight reduction; increased efficiency of main and auxiliary power systems; unconventional air transport of cargo; and operational changes.

INTRODUCTION

The almost complete dependence of transportation systems upon petroleum products makes the transportation sector vulnerable to increased prices and insecure sources of petroleum. At present, the transportation sector of the U. S. economy annually accounts for about 25 percent of the national energy demand, more than 98 percent of it from petroleum. Commercial aviation's share of the transportation demand is currently 14 percent (12 billion gallons of petroleum-based fuel) and has been projected to increase to about 37 percent in the year 2000 (115-160 billion gallons when a projected unconstrained increase in air transportation, particularly cargo, is included). Technological aircraft improvements and changes in operational procedures, however, have the potential to significantly reduce aviation's projected fuel demand and to permit the greater use of nonpetroleum-based fuel.

The airlines are already implementing fuel-conservation changes in operating procedures for current aircraft and consideration is being given to the near-term application of current technologies that could further reduce fuel consumption. The focus of this paper is centered on the fuel-conservation possibilities attainable through the application of advances in aeronautical technology to future aircraft design, although instances will be indicated where the utilization of NASA capabilities to the near-term problem may be desirable. The future use of alternate fuels such as synthetic petroleum,

hydrogen, and methane is the subject of other planning documents and is not considered herein.

NASA is currently pursuing technological improvements in various aircraft disciplinary areas (identified and evaluated in the Advanced Transport Technology Systems and Design Studies) with which subsonic transports of the mid-1980's can be made quieter, less polluting, more profitable, and able to reduce terminal-area delays. These technologies, which include advanced aerodynamics, advanced materials, active controls, advanced propulsion, advanced avionics, and advanced auxiliary systems, were also indicated to provide significant fuel savings (up to 20-30 billion gallons of petroleum fuel per year by the year 2000) even though emphasis was not placed on the fuel-consumption aspects of design. By designing with fuel conservation as a criterion, further fuel savings appear possible. A systems and design study, therefore, is being planned which would: (1) explore these fuel-conserving design opportunities; (2) quantitatively establish tradeoffs among fuel conservation, reductions in noise, pollution, and delay, and economics; and (3) identify critical research and technology requirements.

Potential design parameters judged to have significant impact on fuel use will be assessed. Areas to be evaluated include wing planform (sweep, aspect ratio, thickness, area, wing-fuselage blending), airframe structural design concepts, engine type and cycle, cruise Mach number, payload, and operating procedures. An "Energy-Conservation" aircraft will be conceived and configured and assessments made of potential fuel savings and economics (in terms of today's and projected petroleum-fuel costs). Evaluations should also be made of the energy savings achievable through the use of advanced manufacturing processes (e.g., composites versus aluminum).

Although some recommendations for increased R&T activities in the previously identified technology areas are included in the subsequent text, emphasis is placed on additional possibilities for fuel conservation and associated design study or R&T requirements. The material is organized in the following major categories: drag reduction; weight reduction; increased efficiency (SFC) of main and auxiliary power systems; unconventional air transport of cargo; and operational changes.

An indication of the relative significance of airframe drag, structural weight, and propulsive efficiency and weight on fuel consumption is presented in figure 1. These data were obtained from a parametric study in which the technology parameters were varied from nominal values of current wide-body technology levels. Essentially, each individual technology parameter was systematically changed while the remaining parameters were held at their nominal level, thereby indicating the sensitivity of the airplane design to the individual parameter. No attempt was made to resize the airplane designs and other analyses indicate that the sensitivity of the final design to the technology parameters could be different from that presented when resizing is considered in figure 1. For example, figure 1 indicates that a ten percent improvement in L/D reduces fuel consumption five percent more than an equivalent improvement in SFC. When resizing effects are accounted for, however,

the fuel decrement due to the L/D improvement is about 20 percent greater than that due to the SFC improvement.

DRAG REDUCTION

Skin Friction

During cruise of current subsonic transport aircraft, approximately one-half of the power required to maintain level flight is required to overcome boundary-layer skin friction. Because approximately 69 percent of the fuel used on a transcontinental trip is consumed during cruise, development of means for reducing skin friction will offer significant potential for fuel conservation. The magnitude of the skin friction depends strongly on the boundary-layer state which may be "laminar" or "turbulent", the latter causing a much larger friction force. On current aircraft, the boundary layer is virtually always turbulent. Promising concepts are available for either reducing the magnitude of the turbulent skin friction or for maintaining extensive regions of laminar flow.

Laminar flow control.- Prevention of boundary-layer transition from the laminar to the turbulent state can reduce skin friction by as much as 90 percent. In terms of fuel savings, maintenance of laminar flow on the wing and tails of a long-range transport can reduce fuel consumption by 30 percent.

Of the possible methods for preventing boundary-layer turbulence, only the technique of suction through the airplane skin has proven successful (preferably through a porous surface but also through narrow spanwise slots). The basic theory is well established, verified in wind-tunnel tests, and demonstrated in actual flight with a slotted wing in the 1960's. No applications have been made to either commercial or military aircraft, however, because the technology for economic application was inadequate and the fuel cost savings in itself did not warrant the required development at that time. Examples of the technology deficiencies were the high cost of manufacturing sufficiently smooth slotted surfaces in the absence of lightweight porous material, an anticipated high cost of maintaining sufficiently smooth surfaces, and excessive suction-system weight. Now, however, advances in related technologies offer promise of solution to the practical and cost problems and, in view of the increased emphasis on the need to conserve fuel, suggest that the possible application of laminar-flow control to long-range transport aircraft be reevaluated. Advanced technologies that improve the feasibility of LFC are: (1) woven graphite-epoxy fibers for lightweight porous surfaces; (2) laser drilling of suction holes of a fineness theretofore unattainable; (3) newly-developed chemical coatings for practical removal of dirt and insects; (4) composite materials for lightweight air ducting; and (5) integration of LFC system with one or more auxiliary system, such as auxiliary power units, high-lift boundary-layer control, and air-cushion landing gears.

The initial activity required is a systems and design study of an LFC transport, utilizing the experience of the previous ground and flight tests

and considering the application of advanced technologies. This study will evaluate the current technical and economic feasibility of LFC, estimate the fuel savings achievable with a practical LFC configuration, and identify further R&T tasks if the study results appear promising.

Turbulent skin-friction reduction.-

Surface injection of air: Theory and limited experiments at supersonic and hypersonic speeds indicate the possibility of an appreciable reduction in turbulent skin friction where air is injected into the boundary layer through slots or porous surfaces. Further analytical and wind-tunnel studies of the concept is required at subsonic speeds.

Compliant walls: Several low-speed studies have indicated the possibility of significant reductions in turbulent skin-friction through use of wall materials which respond in an interactive manner to the fluid motions in the boundary layer. Application of compliant surfaces to all aircraft surfaces, if technically possible, might reduce fuel consumption 15 percent. Development of this concept is in a very preliminary stage with several important unknowns: an understanding of the basic mechanism, required material properties, and three-dimensional effects. A basic research program is underway within NASA on the behavior of compliant walls at supersonic speeds and at National Bureau of Standards (funded by NASA) on the basic mechanism involved at low speed. An increased emphasis at subsonic speeds appears appropriate. It should be noted that successful application of compliant surfaces for drag reduction should also reduce the aerodynamic noise emitted from the turbulent boundary layer.

Surface injection of liquid air drops: Studies have indicated that the presence of solid particles in a turbulent boundary layer will decrease skin friction 20 to 40 percent. Carrying particles on board aircraft for this purpose would not only negate the fuel savings possible but would most likely violate anti-pollution requirements. If, however, future aircraft utilize hydrogen fuel, an appreciable heat sink will be available for liquefaction of air droplets which could then be injected into the boundary layer. The combined effects of air injection (previously discussed), particle presence, and particle vaporization may provide a net drag reduction. A small effort is underway in NASA to investigate this possibility experimentally and should be continued.

Component Drag

Although the fuel used by a long-range aircraft during the takeoff and climb-out modes of operation is appreciably less than that consumed due to skin friction during cruise, any decrease in drag accompanied by increased lift-drag ratio attainable through improved high-lift systems will be reflected in a significant fuel savings. Analytical programs are currently being developed for two-dimensional optimization of high-lift flaps. Additional research is required to apply these methods, as well as various boundary-layer control

concepts, in improving the performance of three-dimensional high-lift systems and to validate estimated performance in wind-tunnel tests. Success in this program will also provide a decrease in the aerodynamic noise.

Many current transport aircraft have protuberances, such as lights and exposed windshield wipers; regions of separated flow in cruise, perhaps over the aft-fuselage boattail; and manufacturing irregularities, such as skin gaps and forward- and aft-facing steps; all of these contribute to drag and fuel consumption. Perhaps a joint industry-NASA program should be undertaken to identify and quantify potential drag contributions that could be eliminated with relatively simple changes; e.g., use of vortex generators in separated regions (which would require some wind-tunnel testing) and filling of skin gaps. Results would be applicable not only to derivatives of current aircraft and perhaps to the current aircraft fleet through limited retrofit but also to future aircraft design. It should be noted that the use of composite skin for future aircraft offers the potential for eliminating the drag contribution of the previously indicated manufacturing irregularities at lower cost.

WEIGHT REDUCTION

Auxiliary Systems

The possibilities for weight reductions in auxiliary systems have been examined in the ATT system studies. Typical benefit analyses show savings in iterated takeoff gross weights on the order of four to five percent from application of advanced technologies. Improvements in hydraulic systems, electrical systems, and pneumatic, air conditioning and protective systems are found to offer potential weight reductions of 0.5 percent, 1.1 percent, and 2.8 percent, respectively. Because of the importance of weight reduction on fuel consumption (figure 1), it appears appropriate that the government, through NASA, support the development of these systems with needed design studies and test programs.

Acoustic Composite Nacelle

A national objective is to reduce the noise of transport aircraft that may be introduced into service in the mid-1980's to at least 10 EPNdB below the current Federal Aviation Regulation, Part 36. Achievement of this goal with current technology in the form of acoustic absorbent material applied to engine nacelle duct walls, inlet rings, and splitters results in large penalties in nacelle weight and cost, and in engine performance, and in turn, operating costs and fuel consumption. The effect on fuel consumption of propulsive system noise reduction with current technology is indicated in figure 2.

Recent developments in a more effective noise-attenuation concept (segmented liner) and in interwoven lightweight composite materials offer

the promise of achieving the noise objective for derivatives of the current wide-body transports with no economic or fuel consumption penalty, or conversely, these developments offer the possibility of reducing fuel consumption at current noise levels.

A preliminary design study of a transport nacelle utilizing these advances in technology has been initiated and will be supported by research on the segmented acoustic liner concept and on means of structurally integrating composite materials in both acoustic and nonacoustic nacelle regions. When sufficient confidence in the ability to meet the program objectives has been generated, the next step will be the detail design, fabrication, and test of an advanced acoustic composite nacelle. Included will be structural validation tests to the extent required for FAA certification, validation of the noise attenuation, and flight tests in commercial service to provide operating experience required before extensive use of the advanced technologies will be acceptable for either derivatives of the current wide-body transports or for new aircraft designs.

INCREASED EFFICIENCY (SFC) OF MAIN AND AUXILIARY POWER SYSTEMS

Main Propulsive System

Advanced gas turbine engines.- Fuel consumed by advanced gas turbine engines can be reduced through various advances in engine design that provide higher pressure ratio, higher bypass flows through the engine fan and improved turbine cooling. These design changes may involve improved techniques for aerodynamic design of the compressor, turbine, and fan; better materials for higher turbine inlet temperature; reduced turbine-cooling flow through better techniques for design and fabrication of turbine blades; and composite materials for the fan blades. In addition to implementing these R&T activities, it appears appropriate to reappraise an old concept for improved propulsive efficiency; namely, the use of low-energy air in the nacelle inlet to reduce the ram-drag penalty. It has been shown previously that an improvement of two- to four-percent in SFC was attainable but only with an increase in propulsive system weight that more than offset the economic advantage. With the continual increase in fuel cost, however, the economics of the concept may reverse. Further research on the technical feasibility, therefore, appears warranted. Investigations are required on problem areas such as the pressure recovery attainable with boundary-layer inlets, the distortion in the airflow at the engine face, the ability of engines to operate satisfactorily with the measured airflow distortions, and the amount of boattail drag reduction that might be achieved by locating an engine at the rear of the fuselage. Because the low-energy air used to improve the propulsive efficiency may be compatible with the requirements for the turbulent skin-friction reduction concept on page 4, the possibility of combining the two concepts should be investigated.

Improved Efficiencies of existing engine types.- Several potential techniques have been identified for reducing fuel consumption in existing engine

types through design modifications to selected engine components. These modifications may be found suitable not only for new production for current aircraft derivatives but some may be retrofittable to engines in the fleet. Careful consideration is required to determine economic impact of implementing fuel consumption design improvements; a study should be initiated to assess costs and fuel benefits for the following tasks:

Improved engine seals: Ongoing component research and technology with lift-pad seals has shown that the direct replacement of conventional labyrinth seals with lift-pad seals can result in up to two percent reduction in thrust-specific fuel consumption (TSFC) in modern commercial jet engines. Indications are that installation of these new seals in several existing engine types is feasible.

Improved combustors: Current R&T activity to reduce pollution in the wide-body jet engines is expected to result in very high efficiencies at idle and low thrust operating conditions. These high efficiencies can result in fuel savings of about one percent in addition to achieving their primary objectives of pollution reduction. Additional work will be required to insure good altitude relight performance and long life.

Improved tip-clearance control: Current R&T activities show that by reducing existing compressor and turbine tip clearance by about 10 percent, TSFC reductions of about four percent are possible. Additional studies and exploratory development are required to establish practical tip clearance control concepts.

Improved stage efficiencies: Current R&T activities aimed at reducing end wall pressure losses at the blade hub and tip (compressors and turbines) have shown that TSFC reductions of about one percent are possible if the techniques examined for reducing the losses were incorporated in modern jet engines.

Improved cooled turbines: Current R&T activities aimed at improving the air cooling characteristics of high temperature turbines indicate that with minimal additional effort, these concepts can be incorporated in modern jet engines with relatively low risk. TSFC savings of about one percent could result.

Auxiliary Power Unit (APU)

Secondary power systems in past transport aircraft designs were independently developed by design groups with heavy dependence on generally available equipment that requires a minimum of development. Advances in auxiliary power systems offer the possibility of weight savings and increased efficiency for a relatively small investment of R and T. Most modern jet transports carry an additional gas turbine that permits operation of certain subsystems on the ground independent of the main engines. For the majority of the flight profile, this engine is dead weight. A recent study of secondary power systems conducted under the ATT program showed a preference for the dedicated auxiliary

power unit (APU) concept. Utilization of an APU power generation system throughout the flight profile offers savings in iterated gross weight, cruise drag and specific fuel consumption. Implementation of the "dedicated APU" system significantly reduces engine-mounted accessories, bleed-air penalties and gear boxes on the main engine thereby decreasing its size, weight, and frontal area. The constant design speed of the APU eliminates the constant-speed drive and offers higher power generation efficiency and smaller power components.

Systems concepts employing powered wheels offer potential fuel savings and are integrally involved in the overall effort of providing the most efficient secondary power system. Advanced concepts should be developed and coordinated with the other technical tasks and objectives in this area. A potentially fruitful study task would be to optimize the APU load profile and power extraction techniques in a manner to minimize fuel consumption and drag while incurring minimum subsystem penalties in complexity, weight and maintenance.

UNCONVENTIONAL AERONAUTICAL SYSTEMS

Fulfillment of a projected appreciable increase in demand for air transportation of cargo may be constrained by a combination of fuel shortage and increased fuel cost. Because current "convertible" aircraft are compromised designs, fuel consumption is penalized for the cargo version by such factors as poor center-of-gravity location which increases fuel consumption due to the need for excessive use of control surfaces. A strong motivation exists, therefore, to consider new "dedicated" cargo aircraft design concepts utilizing the latest technologies.

Since environmental control and electronic equipment would be minimal and since the floor could be designed as a minimum weight structure with an integrated cargo loading system, the design weight of such an aircraft has been shown in preliminary studies to be 25 percent lower than a passenger-rated convertible vehicle of the same exterior dimensions. The importance of weight reduction technology in reducing fuel requirements is reflected in improving the payload weight fraction by reducing vehicle empty weight. For an aircraft, the gain in performance efficiency resulting from decreases in empty weight can be significant (e.g., see figure 1).

The cargo aircraft could be designed to a relatively low cruise speed nearer the optimum velocity for minimum fuel consumption; in contrast to the passenger carriers, there is little demand for high-speed operation of cargo aircraft.

Some fuel savings would result from increasing the size of an all-cargo aircraft over current wide-body designs. Up to some limit, skin-friction drag can be shown to decrease as aircraft size increases (about 10 percent reduction in skin friction by doubling aircraft size). If a cargo aircraft design

could evolve around the optimum size to minimize parasite drag, then fuel savings would result.

An in-house preliminary design effort is underway to identify likely configuration alternatives. In addition to single aircraft concepts, these studies will also review applications of novel concepts for all-cargo transportation. Tip-coupled aircraft, gliders, and composite aircraft (utilizing "mother-ship" concept) will be included in this category. Airframe contractor support of these in-house studies will be required.

To maximize the benefits from an advanced cargo transportation system, these new aircraft concepts must be properly integrated with ground handling systems dedicated to cargo operations and must successfully interface with other transportation modes. The utilization of containerized cargo will further enhance the efficiency of the air cargo system. The increased cargo densities and load factors possible with such advanced transport systems will greatly increase the ton-miles of air cargo transported for a given fuel dollar, and could substantially reduce the total fuel expended in the transportation network in delivering a product from the producer to the consumer. To evaluate these broader implications to the market system and to assess related socio-economic, political and legal ramifications of all-cargo aircraft systems, a technology assessment will be carried out concurrently in collaboration with the National Science Foundation.

Air-Cushion Vehicle (ACV) and Lighter-Than-Air (LTA) Vehicle

Potentially, a significant portion of the increased cargo transportation demand could be met with the use of "unconventional" means of air transport, such as the Air-Cushion Vehicle (ACV) and the Lighter-Than-Air (LTA) vehicle. These air systems promise the efficient movement of large cargo volume and weight and offer apparently attractive alternatives to the increasing use of higher speed aircraft. It has been estimated, for example, that for equivalent ton-mile productivity compared with a modern large conventional transport airplane, the ACV and the LTA could require only 1/4 and 1/8 of the fuel, respectively. Additionally, these concepts minimize the need for construction of new or modified right-of-way facilities essential for the expansion of rail and truck modes and may reduce the terminal requirements associated with high-performance airplanes.

Present technology generally is sufficient to permit construction and experimentation with any of these approaches, but possibly not to permit economically viable operation in commercial service. The economic feasibility, and the degree of advancement in technology required, must be determined from systems studies including comparison with other competing transportation modes. Also to be considered prior to a development decision is the selection of the most appropriate fuel. All of the approaches are "volume rich" in that they will have sufficient space available to consider either the use of methane or hydrogen as a fuel. In addition, due to the low power requirement and the high payload potential of these vehicles, they are prime candidates for the application of a nuclear propulsion system.

Currently the ACV and LTA concepts are not being actively pursued. A small in-house effort is planned to assess the impact of current technologies in dirigible design; an adequate understanding of LTA characteristics will require a more in-depth industry study. Systems and design studies should also be initiated on the technical and economic feasibility of the ACV concept.

Over The Wing Blowing (OWB)

Significant engine noise reduction can be attained by mounting engine nacelles on the upper wing surface or by integrating the nacelle with the wing to allow exhaust to pass over the upper surface. This design can also be beneficial through lift augmentation during ascent and descent. In cruise operation, however, a drag penalty may occur due to the placement of the nacelles in the high velocity field of the upper surface. As part of an ongoing wind-tunnel investigation of wing-mounted nacelle installations, plans are being formulated to investigate means for reducing the drag of over-the-wing nacelle arrangements.

OPERATIONAL CHANGES

Optimum Profile

Airline adoption of optimum flight profiles could save about five percent of total fuel consumption by making use of high-capacity computers to define flight paths which are optimum from an energy standpoint. The basic principal is to spend more flight time at cruise altitude where fuel economy is greatest. About half the savings come from climbing at slower speeds but steeper angles in order to quickly reach cruise altitude. Optimum selection of speeds and altitudes for particular flight segments would account for the rest of the savings. For reference, a current aircraft's fuel consumption schedule is as follows for an idealized cross-country flight:

Taxi and takeoff fuel	1.2%
Climb	11.5%
Cruise	69.0%
Descent	0.6%
Reserve	17.7%

The fuel savings indicated by optimizing flight profiles are currently seldom realizable because of limitations in the air traffic control system (ATC) and by ground traffic delays. The importance of NASA support of DOT/FAA activities in improving ATC and the aircraft/airport interface, therefore, is reemphasized.

Advanced Two-Segment Approach (90/30)

As indicated on Page 5, application of an advanced acoustic treatment concept and composite materials to engine nacelles offers the promise of reducing propulsive noise of derivatives of the wide-body fleet to 10 EPNdB below the noise levels described in the current Federal Aviation Regulations, Part 36, with no economic or fuel consumption penalty. This noise reduction translates into a greater than 30 percent reduction in the area on the ground subject to an approach noise level of no more than 90 EPNdB. The use of steep, two-segment approaches has been shown to offer the potential for an equivalent reduction in approach noise footprint area for future aircraft designs but with little effect on the noise at the FAR 36 measuring points. Because the noise footprint area may become a regulatory criterion in the future and because it has not yet been shown whether footprint reduction through noise abatement at the source or by steep approaches is more economical and fuel conservative for new designs, a design study is needed to perform tradeoff analyses of the two candidate approaches. A number of combinations of source-noise reduction and steep approach should be evaluated in terms of noise contours, fuel consumption, economics, and safety.

TECHNOLOGY PARAMETERS

- W_S/W_l (structure to landing weight ratio) 0.427 nominal
- - - - L/D (cruise lift to drag ratio) 15.1 nominal
- η_p (propulsive efficiency) 0.293 nominal
- W_p/Thrust (power plant installed weight ratio) 0.307 nominal

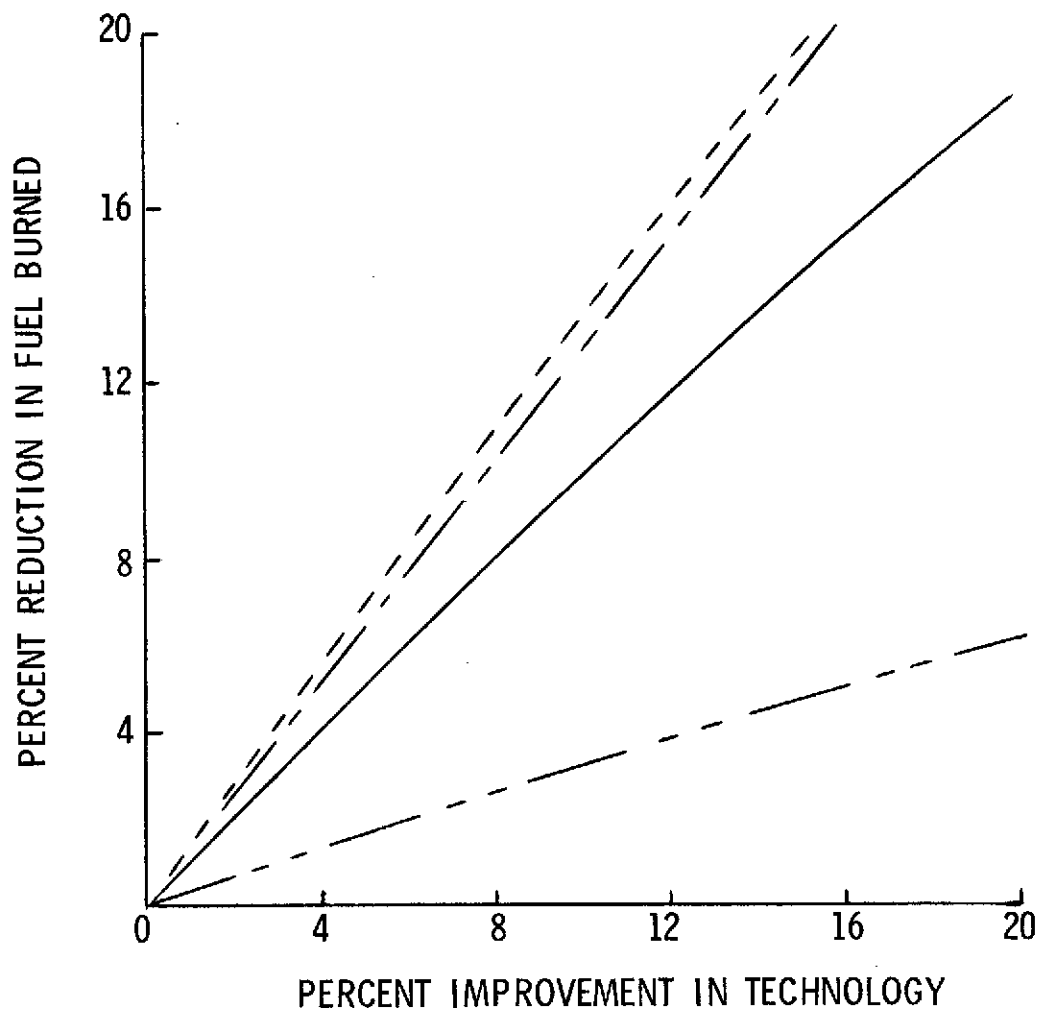


Figure 1. - Typical subsonic transcontinental airplane

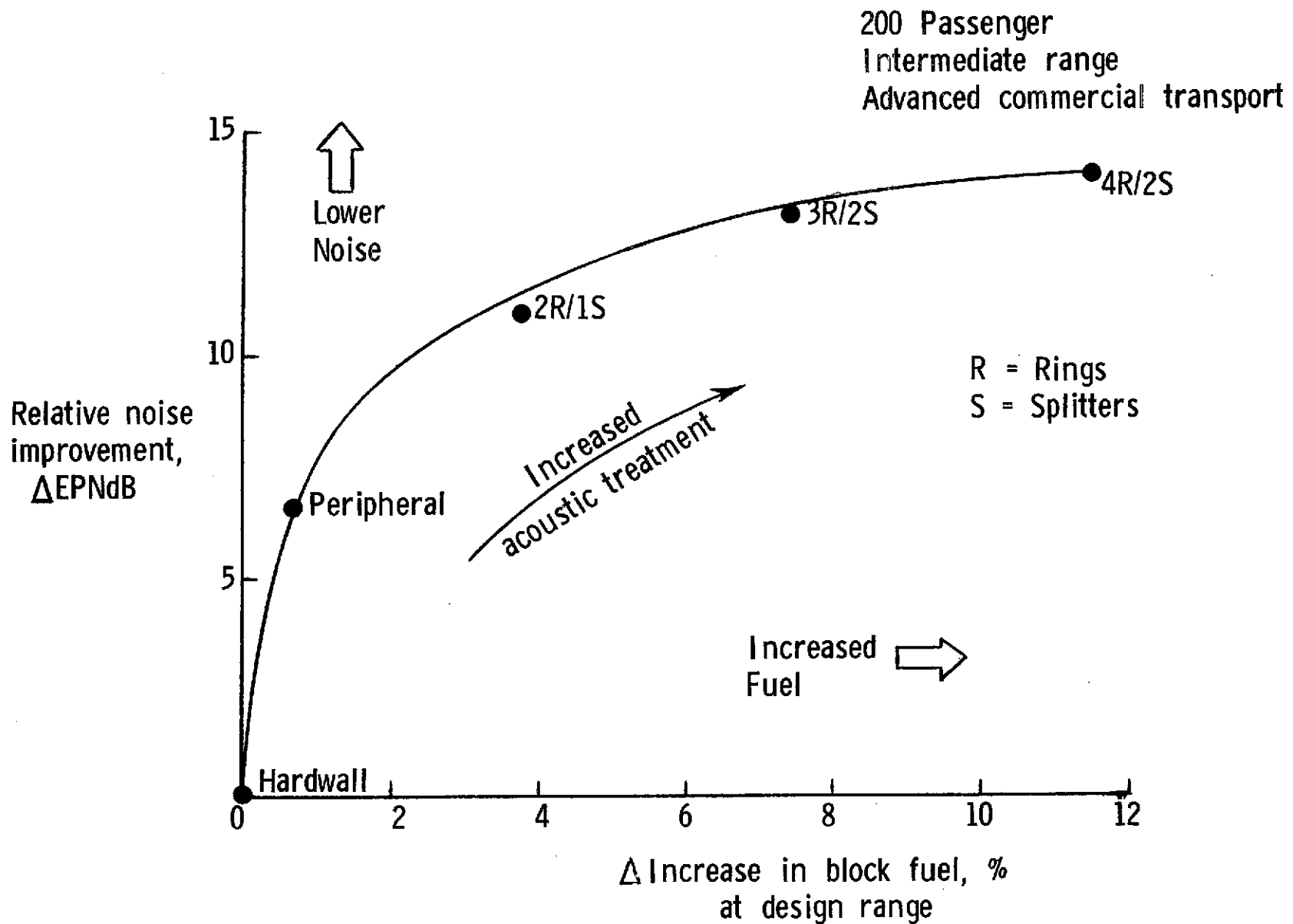


Figure 2. - Energy implications of noise reduction